Journal of Power Sources 257 (2014) 12–20

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

The impact of range anxiety and home, workplace, and public charging infrastructure on simulated battery electric vehicle lifetime utility

Jeremy Neubauer*, Eric Wood

National Renewable Energy Laboratory, 15013 Denver West Parkway, Golden, CO 80401, USA

HIGHLIGHTS

- Applies real-world climate and driver data, validated vehicle and battery models.
- Quantifies effects of driver range anxiety and home, workplace, and public charging.
- Effects of range anxiety can be significant, but are reduced by charging infrastructure.
- Increased home charge power beyond a 15 A, 120 V circuit offers little added utility.
- Public charging can greatly increase utility for many drivers.

ARTICLE INFO

Article history:
Received 27 November 2013
Received in revised form
16 January 2014
Accepted 18 January 2014
Available online 25 January 2014

Keywords:
Battery Lifetime Analysis and Simulation Tool for Vehicles
Range anxiety
Electric vehicle
Workplace charging
Public charging
Fast charging

ABSTRACT

Battery electric vehicles (BEVs) offer the potential to reduce both oil imports and greenhouse gas emissions, but have a limited utility due to factors including driver range anxiety and access to charging infrastructure. In this paper we apply NREL's Battery Lifetime Analysis and Simulation Tool for Vehicles (BLAST-V) to examine the sensitivity of BEV utility to range anxiety and different charging infrastructure scenarios, including variable time schedules, power levels, and locations (home, work, and public installations). We find that the effects of range anxiety can be significant, but are reduced with access to additional charging infrastructure. We also find that (1) increasing home charging power above that provided by a common 15 A, 120 V circuit offers little added utility, (2) workplace charging offers significant utility benefits to select high mileage commuters, and (3) broadly available public charging can bring many lower mileage drivers to near-100% utility while strongly increasing the achieved miles of high mileage drivers.

1. Introduction

Battery electric vehicles (BEVs) offer the potential to reduce both oil imports and greenhouse gas emissions, but have a limited range and require significantly more time to recharge than the time required to refuel a conventional vehicle. These factors limit the achievable number of vehicle miles traveled (VMT), negatively impacting the potential gasoline consumption, greenhouse gas emissions, and financial benefits offered by this technology.

Calculating the extent of these limitations is complicated by the fact that the range of the vehicle is sensitive to many factors. Each trip's acceleration and speed characteristics have a direct impact on vehicle efficiency—more aggressive trips will consume more energy from the battery for each mile driven. Use of cabin climate control (e.g., air conditioning) can add considerably to auxiliary load demands placed upon the battery. Battery temperature can affect efficiency and available energy. Further, the battery's ability to store energy degrades in response to these and other factors throughout its service life.

Beyond the variability of single-charge vehicle range, driver range anxiety and the availability of charging infrastructure can also impact achieved VMT. Range anxiety—the fear of fully depleting a BEVs battery in the middle of a trip, leaving the driver stranded—can cause drivers to employ alternative (gasoline consuming) means of transportation even though their BEV is capable of adequately

* Corresponding author. Tel.: +1 720 989 1919.
E-mail addresses: Jeremy.neubauer@nrel.gov, jeremy.s.neubauer@gmail.com (J. Neubauer).

0378-7753/$ – see front matter
http://dx.doi.org/10.1016/j.jpowsour.2014.01.075

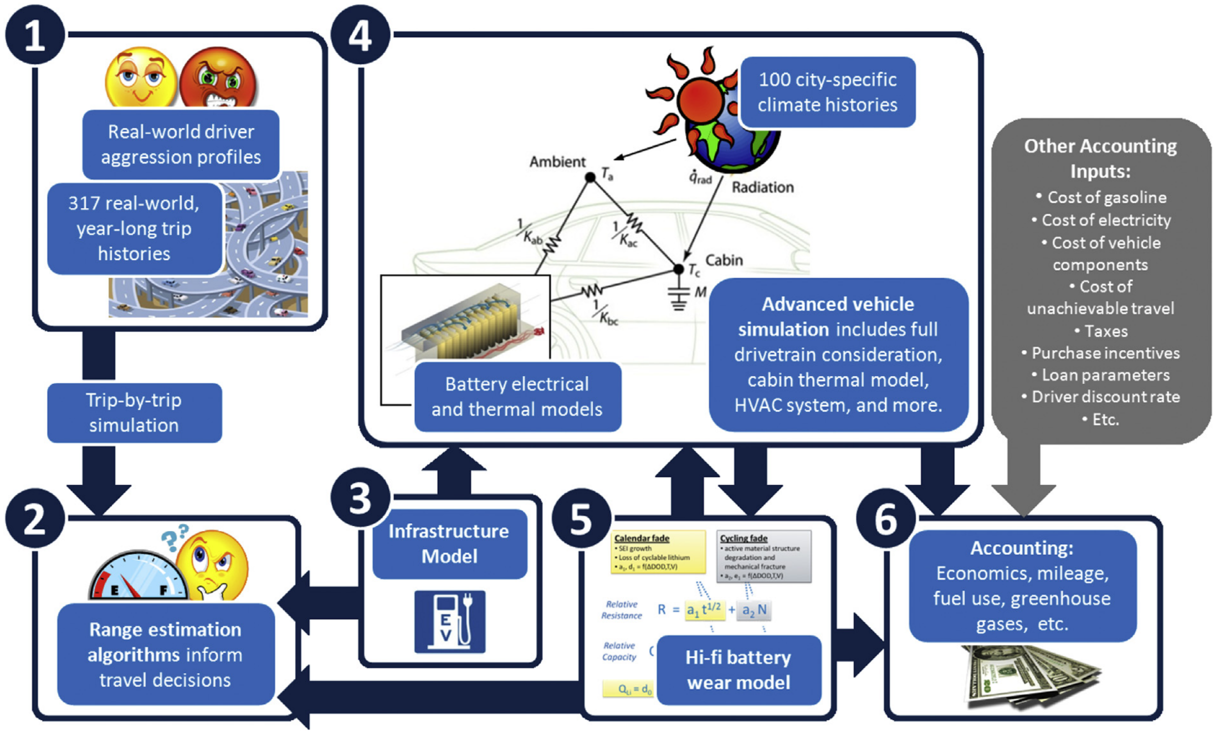

Fig. 1. Graphical illustration of BLAST-V simulation algorithms.

completing their required travel. For example, a driver's range anxiety may encourage them to only take trips less than 90 miles long with a BEV capable of 100 miles, ensuring that they have 10 miles of margin to cover uncertainty in travel distance and energy consumption. Charging infrastructure, on the other hand, can encourage BEV drivers to increase travel distance thanks to the ability to recharge the vehicle away from home. It may also be able to reduce the impact of range anxiety on achieved VMT.

With support from the Vehicle Technologies Office in the U.S. Department of Energy, the National Renewable Energy Laboratory has developed BLAST-V—the Battery Lifetime Analysis and Simulation Tool for Vehicles. BLAST-V is an evolution of NREL's Battery Ownership Model, which is designed to evaluate the total cost of ownership and address other challenges associated with the life-cycle performance of electric vehicles. The Battery Ownership Model has been applied for studying the effects of electric range and charge strategies on both BEVs and plug-in hybrid electric vehicles in past studies [1–4]. BLAST-V improves the resolution of drive patterns to the individual trip level, considering both the temporal and spatial distribution of trips, and adds additional capability to account for the effects of driver aggression, local climate, vehicle cabin thermal management systems, and battery thermal management systems. Further, future development will allow BLAST-V to analyze electrical, electrochemical, and thermal performance variations between cells within a pack. Recently we used BLAST-V to study the impact of driver aggression, climate, cabin thermal management, and battery thermal management on the utility of BEVs [5]. In this paper, we apply BLAST-V's capabilities to examine the sensitivity of BEV utility to driver range anxiety and charging infrastructure over the life of the vehicle.

2. Approach

BLAST-V is an electric vehicle simulator focused on computing long-term effects of complex operational scenarios on vehicle utility and battery performance. It considers the vehicle powertrain, battery control strategy, driving and charging patterns, local climate, the vehicle-battery-environment thermal system, battery chemistry, and other factors in computing short-term vehicle and battery performance (e.g., vehicle range, battery voltage, state of charge (SOC), and temperature) and long-term vehicle utility and battery degradation. An approximate graphical representation of the key elements and flow of data within BLAST-V is illustrated in Fig. 1.

BLAST-V's sourcing and use of climate and driver data are documented in Ref. [5]. In this study we apply the same source of typical meteorological year climate data, battery performance and degradation models, treatment of driver aggression, and mid-size sedan vehicle model from Refs. [5,6]. We restrict this investigation, however, to high-aggression drivers operating a high-feature, ∼75-mile range (window sticker approximation) BEV equipped with air conditioning and heat pump cabin climate control systems, cabin preconditioning (when at an active charger), and a high-power, active battery thermal management system functional in both key-on and standby modes in Phoenix, Arizona. This is based on our expectations of near-future mass-market BEV feature sets along with the intention of increasing auxiliary loads and battery wear, which should increase the sensitivity of our results to different charging infrastructure assumptions.

Table 1
Charger power levels.

Scenario	AC circuit	AC-to-DC efficiency	DC power
Level 1 (L1)	120 V, 15 A	85%	1.5 kW
Level 2 (L2)	240 V, 32 A	85%	6.5 kW
DC fast charging (L3)	480 V, >123 A	85%	50 kW

Table 2
Charger timing scenarios.

Scenario	Available charge hours
Timed	12:00 a.m. to 1:00 p.m.
Opportunity	All hours

2.1. Charger power and availability

Three different power levels are considered for chargers within this study, as listed in Table 1. Two different charger availability schedules are employed, as listed in Table 2. The "Timed" scenario is set to avoid on-peak periods where demand charges and time-of-use energy charges are highest by restricting use of chargers between 1:00 p.m. and 12:00 a.m., such that use of the "Timed" scenario would reduce the aggregate cost of electricity. The "Opportunity" scenario allows drivers to charge their BEVs at any time to increase utility.

Three different location classes are considered for charger placement: home, workplace, and public. Home assigns one charger to a specific location unique to each driver that corresponds to his or her place of residence. This is assumed to be a dedicated charger that is available per the elected charger timing scenario. Implementation of the workplace class is performed identically, with the exception that the charger is located at the driver's place of business. The public class assumes chargers are available per the elected charger timing scenario at every location that is not the driver's place of residence or work. Note that we do not discriminate between commercial and residential locations nor do we consider the possibility that such chargers are unavailable due to use by other drivers. As such, this represents an idealized, best-case scenario with respect to providing drivers access to charging infrastructure.

2.2. Travel simulation

Travel simulation is conducted in an identical manner as is done in Ref. [5]. We begin with a decision by the simulated driver regarding the ability of the BEV to complete the planned trips and return home before depleting the battery. This decision is made at the beginning of each tour (a sequence of trips that begins and ends at home), and considers the current SOC of the battery, the historic efficiency of the vehicle over the past 100 trips, the trip distances to be traveled within the tour, and the charging opportunities between trips. From these data, an estimate of the battery SOC at the end of each trip within the tour is calculated. If it is estimated that the vehicle can complete the tour while maintaining a specified minimum range margin at the end of each trip, then the tour is taken. If not, the BEV is left at home and does not take the tour.

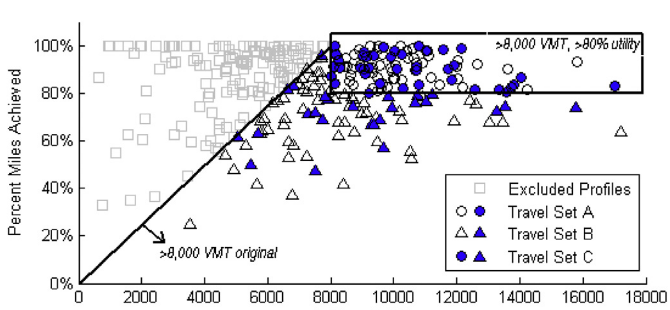

Fig. 2. Utility Factor vs. Achieved VMT of trip histories from the Puget Sound Regional Council's Traffic Choices Study.

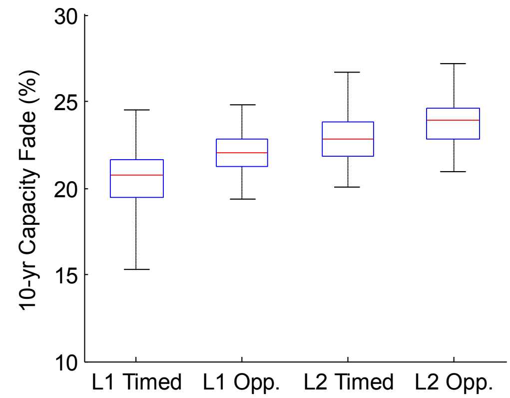

Fig. 3. Battery capacity loss at end of year 10; low range anxiety (5-mile minimum range margin).

We employ the minimum range margin as a proxy for range anxiety. The assumption of perfect knowledge of future trip timing, distances, and charger availability combined with an accurate forecast of vehicle performance minimizes the likelihood that a simulated driver will be stranded and thereby discourages range anxiety and encourages use of a small minimum range margin. However, in the real world, driver access and response to this information will vary. To examine the sensitivity to these effects, we apply two different minimum range margins to our studies: 5 miles to represent high quality information and low range anxiety, and 15 miles to represent low quality information and high range anxiety.

Another point pertaining to tour decisions that it is important to highlight is that this study does not assume that driver travel behavior is altered in response to charger infrastructure availability beyond the election of taking a specific tour. While tour decisions consider the effect of available infrastructure on battery SOC over the course of the original trip and park sequence, reordering events within a tour, redistributing trips between different tours, extending park events, and other strategies that could increase utility are not considered.

Once a tour is elected, we simulate each drive and park event in order per the elected tour's trip-park sequence. Average and root mean square battery power of drive events are calculated as a function of trip duration and distance. Charge event power is calculated as a function of the state of the battery and the definition of the charging infrastructure. Both battery electrical and battery and cabin thermal response are simulated, taking into consideration local climate, cabin thermal management system response,

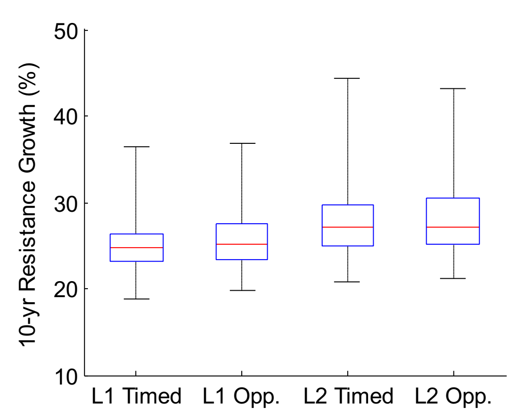

Fig. 4. Battery resistance gain at end of year 10; low range anxiety (5-mile minimum range margin).

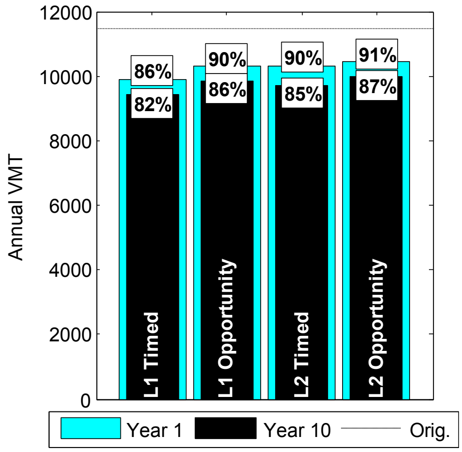

Fig. 5. Average utility achieved by travel set A across four different home charging scenarios; low range anxiety (5-mile minimum range margin).

and battery thermal management system response, with a 1 min time step.

2.3. Trip history down selection

It is unreasonable to expect that our ∼75-mile range (approximate window-sticker rating) BEV is a practical option for all trip patterns due to its limited range. Accordingly, we wish to focus our study on only those trip histories that are most amenable to the capabilities of this vehicle. To do so, we simulate 317 year-long trip histories from the Puget Sound Regional Council's Traffic Choices Study [7] using a normal aggression driver, the absence of active cabin and battery thermal management systems, the Los Angeles climate, and timed home L2 charging. We then select trip patterns that yield a year-one VMT ≥8000 miles and a utility factor (defined as VMT achieved divided by VMT desired) ≥80%. Fig. 2 shows the 91 of 317 trip histories that meet these criteria (27%) as circles. We shall refer to these 91 trip histories as travel set A.

We then expand this set by eliminating the requirement that drivers achieve a utility factor >80%, on the basis that the infrastructure scenarios we deploy herein may enable the high-mileage drivers excluded from set A to achieve high utility factors and thereby become likely BEV drivers. This adds 89 more trip histories, shown as triangles in Fig. 2, which we refer to as travel set B.

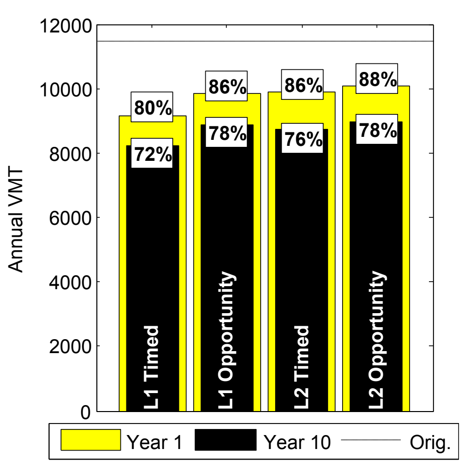

Fig. 6. Average utility achieved by travel set A across four different home charging scenarios; high range anxiety (15-mile minimum range margin).

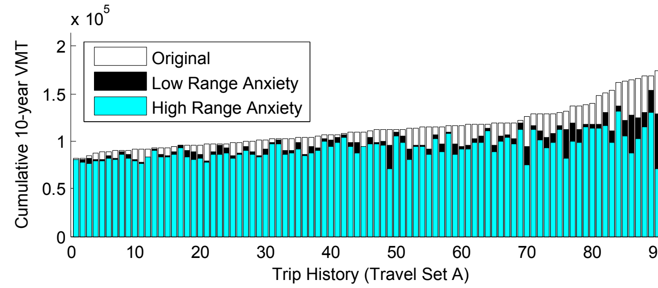

Fig. 7. Cumulative VMT over 10 years for individual drivers with low (5-mile minimum range margin) and high (15-mile minimum range margin) range anxiety; L1 opportunity home charging only.

Finally, we create travel set C to capture high mileage commuters specifically. This is done by filtering the 180 trip histories of travel sets A and B based on the number of trips to work per year. The resultant 68 trip histories that made at least one trip to work on 200 days per year or more are included in travel set C, shown as blue shaded circles and triangles in Fig. 2.

3. Results

3.1. Home charging

We first assess the impact of four different at-home-only charge strategies: L1 and L2 timed and opportunity charging. We restrict our investigation to travel set A only. Figs. 3 and 4 show the battery capacity loss and resistance gain, respectively, at the end of year 10 for low range anxiety drivers. The box plots show the minimum, 25th percentile, median, 75th percentile, and maximum values across travel set A.

The total utility for these cases is shown in Fig. 5 for low range anxiety drivers. The colored bars show the total VMT achieved in year 1 when averaged across all 91 travel set A drivers. The overlaid black bars show the year 10 utility. These can be compared to the dashed line at 11,470 miles, which represents the original average VMT when completed in a vehicle that is not range restricted.

These results show that the utility of our ∼75-mile BEV is largely unaffected by the variation in home charging strategies, with the exception that use of L1 timed charging can limit achieved mileage. It is worthwhile to note that these data also suggest home access to an L2 charger is not a prerequisite for BEV ownership, as L1 opportunity

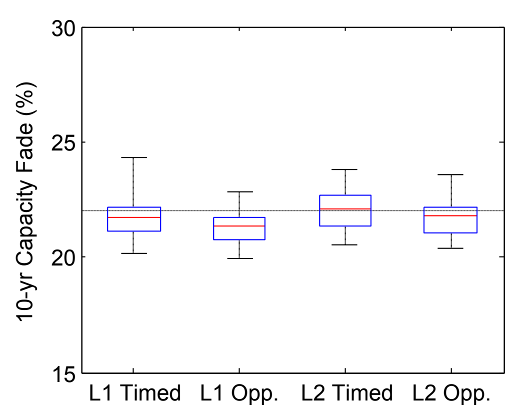

Fig. 8. Battery capacity loss at end of year 10 with L1 opportunity charging at home and one of four different at-work charging strategies; low range anxiety (5-mile minimum range margin). Dotted line represents median capacity loss with home-only L1 opportunity charging for travel set C.

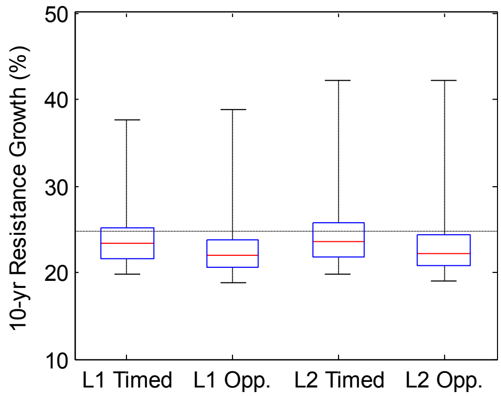

Fig. 9. Battery resistance gain at end of year 10 with L1 opportunity charging at home and one of four different at-work charging strategies; low range anxiety (5-mile minimum range margin). Dotted line represents median resistance growth with home-only L1 opportunity charging for travel set C.

charging yields an average utility factor similar to that of L2 opportunity charging, and higher than that of L2 timed charging. L1 opportunity charging also results in less battery wear than either of the L2 cases due to a slightly lower average SOC through life.

Now we turn to the investigation of the impact of increased range anxiety (15-mile minimum range margin). We find that the battery wear for high range anxiety drivers is exceedingly similar to that of low range anxiety drivers. Utility, however, is affected. Fig. 6 shows the year 1 and year 10 achieved VMTs for high range anxiety drivers when averaged across travel set A for all four charging strategies. We observe that the increased range anxiety decreases year 1 and year 10 utility by ~6% and ~9%, respectively, irrespective of charge strategy. In Fig. 7, we plot cumulative VMT for each driver in travel set A individually to compare original VMT, achieved VMT as a low range anxiety driver, and achieved VMT as a high range anxiety driver when L1 opportunity home charging is employed. This shows that the effect of range anxiety is coupled with the drive pattern: while many drivers see relatively small impacts of the increased minimum range margin, select drivers can see a significant reduction in achieved mileage when range anxiety is increased.

3.2. Workplace charging

Next we study the benefits of adding a dedicated workplace charger on set C travel histories. Based on our findings in Section 3.1

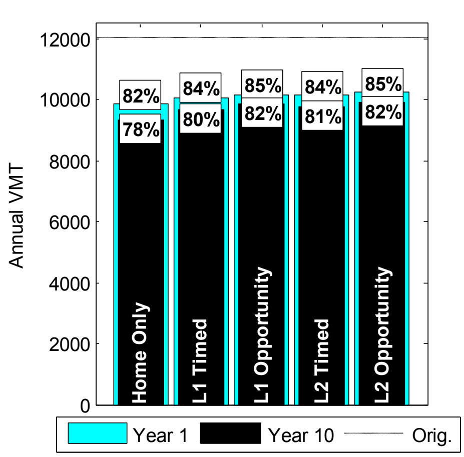

Fig. 10. Average utility achieved by travel set C for home-only L1 opportunity charging, and home-only L1 opportunity charging plus four different work charging scenarios; low range anxiety (5-mile minimum range margin).

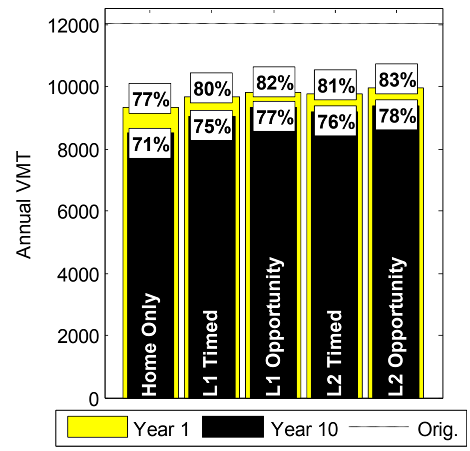

Fig. 11. Average utility achieved by travel set C for home-only L1 opportunity charging, and home-only L1 opportunity charging plus four different work charging scenarios; high range anxiety (15-mile minimum range margin).

we shall assume that L1 opportunity charging is employed at home. We vary workplace charging across all combinations of L1, L2, timed, and opportunity charging. While timed charging significantly reduces the number of hours workplace charging may be used, it is included to acknowledge that many workplaces may be sensitive to adding significant amounts of charging loads during on-peak hours.

Figs. 8 and 9 show the battery capacity loss and resistance gain at the end of year 10 for the low range anxiety driver. Compared to the battery wear reported for L1 home opportunity charging alone, these results generally show a slight decrease in capacity loss and resistance growth, likely due to the decrease in average cycle depth. Degradation for the high range anxiety driver (not shown) is similar.

Figs. 10 and 11, formatted identically to Fig. 5, present our results of achieved VMT for low and high range anxiety drivers, respectively. We notice only slight improvements in utility factor with the addition of at-work charging for low range anxiety drivers (up to +3% in year 1 and +4% in year 10). For high range anxiety drivers, the additional utility achieved is larger (up to +6% in year 1 and +7% in year 10), but the overall impact is still small and the achieved utility is still significantly less than 100% when averaged across drivers of travel set C. We also notice that variation in at-work charging strategy has little effect on average achieved VMT. The similarity between timed and opportunity cases may suggest that the morning hours alone are sufficient for recharging the fraction of the battery depleted from the morning commute, and that mid-day travel prior to the evening commute is largely inconsequential to overall utility.

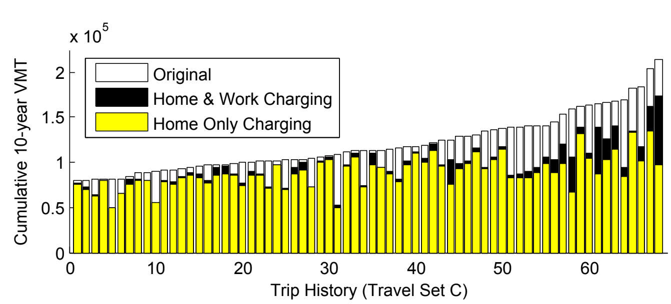

Fig. 12. Cumulative VMT over 10 years for individual high range anxiety (15-mile minimum range margin) drivers with and without L2 opportunity workplace charging.

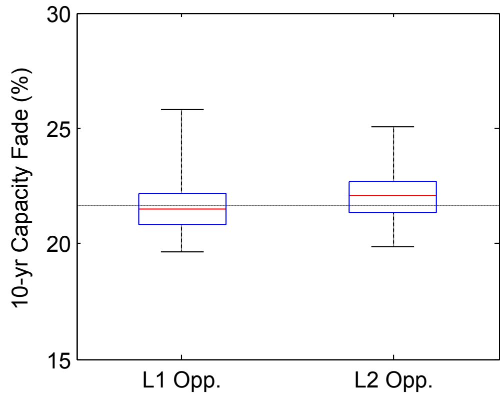

Fig. 13. Battery capacity loss at end of year 10 with L1 opportunity charging at home and one of two different public charging strategies for travel sets A and B; low range anxiety (5-mile minimum range margin). Dotted line represents median capacity loss with home-only L1 opportunity charging for travel sets A and B.

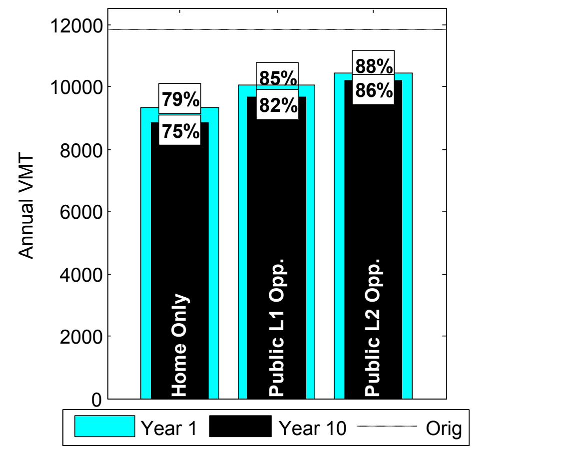

Fig. 15. Average utility achieved by travel sets A and B across two different public charging scenarios with L1 opportunity charging at home; low range anxiety (5-mile minimum range margin).

Looking at results for individual trip histories under the high range anxiety assumption in Fig. 12 (home L1 opportunity plus at-work L2 opportunity) shows that the majority of the observed utility benefit comes from a small number of high-mileage commuters. Further, this disparity increases slightly when range anxiety is reduced. This may suggest that most long distance travel days do not coincide with days where considerable time is spent at work, or that the additional range provided by work charging—limited largely to the distance of the morning commute—is not sufficient to cover extended after-work travel distances. Despite its apparent lack of broad applicability, it appears that workplace charging may be justified when provided to the right driver, as our highest mileage trip history achieved ~77,000 additional miles over the simulated 10-year period when at-work L2 opportunity charging was made available.

3.3. Public charging: L1 and L2

Here we study the benefits of broadly accessible L1 and L2 public charging on travel sets A and B. Recall from Section 2.1 that this classification of charging infrastructure provides drivers with access to a charger everywhere they park that is not defined as their home or workplace. Based on our findings in Sections 3.1 and 3.2, we shall assume that L1 opportunity charging is employed at home, and there is no access to workplace charging. We employ L1 and L2 power levels under the opportunity timing schedule. We exclude the timed charging schedule on the assumption that it will marginalize the benefit of public charging and is unlikely to be implemented in practice.

In Figs. 13 and 14 we present the battery degradation for these public charging strategies. We note that the capacity loss and resistance gain for the middle 50% of trip histories does not change substantially between these public charge options or in comparison to the home-only L1 opportunity charging results of Figs. 3 and 4.

We present our results of achieved VMT for travel sets A and B low and high range anxiety drivers in Figs. 15 and 16, respectively. Here we see significant improvement in year 1 and year 10 achieved VMT with the addition of public L1 and L2 opportunity charging. The increased power of L2 charging also shows a clear benefit over that of L1. High range anxiety drivers see a slightly larger benefit to public charging, and with public L2 charging coming within 3% of the average year 10 utility achieved by low range anxiety drivers.

The cumulative achieved VMT of high range anxiety drivers with and without public charging is shown in Fig. 17. Unlike with the addition of workplace charging, the benefit of public charging is

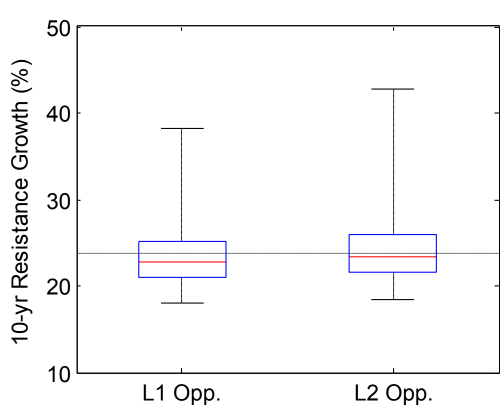

Fig. 14. Battery resistance gain at end of year 10 with L1 opportunity charging at home and one of four different public charging strategies for travel sets A and B; low range anxiety (5-mile minimum range margin). Dotted line represents median capacity loss with home-only L1 opportunity charging for travel sets A and B.

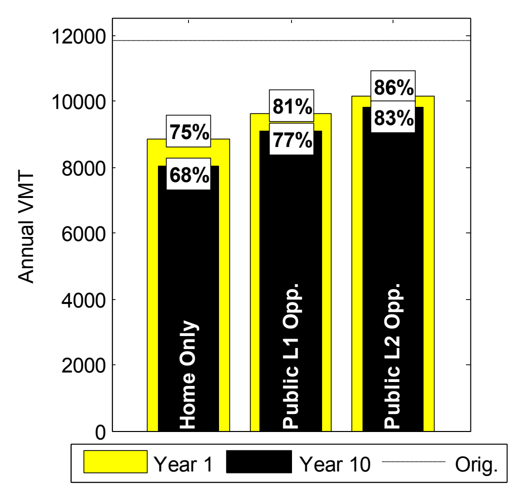

Fig. 16. Average utility achieved by travel sets A and B across two different public charging scenarios with L1 opportunity charging at home; high range anxiety (15-mile minimum range margin).

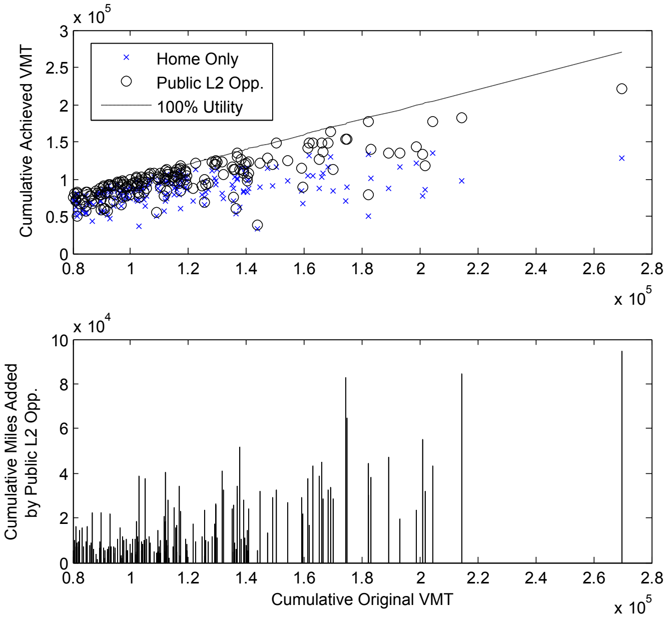

Fig. 17. Cumulative VMT over 10 years for individual high range anxiety (15-mile minimum range margin) drivers in travel sets A and B with and without public L2 opportunity charging.

more evenly spread across drivers, although high mileage drivers generally reap more benefit. Further, many drivers come close to achieving a 100% utility factor with the use of ubiquitous public L2 charging infrastructure.

3.4. Public charging: DC fast charging (L3)

Finally, we study the benefits of broadly accessible public DC fast charging (L3) on travel sets A and B. Recall from Section 2.1 that this classification of charging infrastructure provides drivers with access to a charger everywhere they park that is not defined as their home or workplace. Based on our findings in Sections 3.1 and 3.2, we shall assume that L1 opportunity charging is employed at home, and there is no access to workplace charging. We employ opportunity and a modified timed schedule for public DC fast charging (L3) availability. The modified timed schedule attempts to reconcile the need of the provider to both reduce demand charges while also offering 24/7 charger access by allowing full L3 power from 12:00 a.m. to 1:00 p.m., but reduced L2 power from 1:00 p.m. to 12:00 a.m.

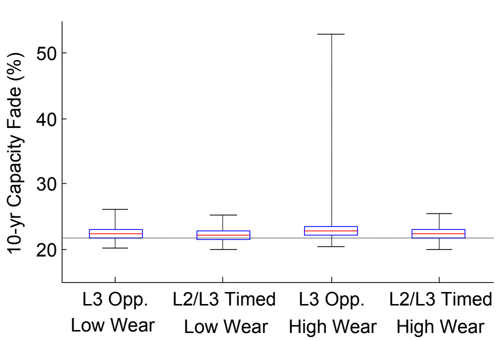

Fig. 18. Battery capacity loss at end of year 10 for four public charging scenarios; travel sets A and B; L1 opportunity home charging; low range anxiety (5-mile minimum range margin). Dotted line represents median capacity loss with home-only L1 opportunity charging for travel sets A and B.

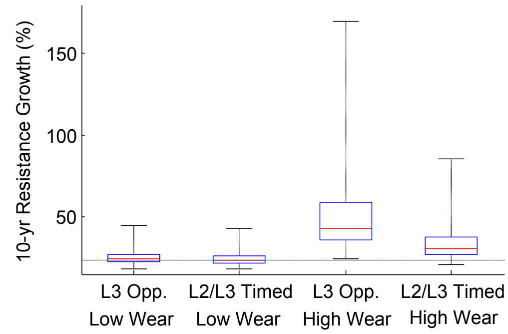

Fig. 19. Battery resistance growth at end of year 10 for four public charging scenarios; travel sets A and B; L1 opportunity home charging; low range anxiety (5-mile minimum range margin). Dotted line represents median capacity loss with home-only L1 opportunity charging for travel sets A and B.

In addition, to address sensitivity to the additional battery wear imposed by fast charge cycles, we include an amplification factor that increases the degradation imposed by the fast charge cycles by a factor of 10. Due to a lack of understanding of how fast charging affects degradation of battery chemistry employed herein, this value has been arbitrarily selected simply to demonstrate the possible impacts of additional battery wear that may result from fast charging.

Beginning with battery wear, we first present the year 10 capacity loss and resistance gain in Figs. 18 and 19, respectively. These data are for the low range anxiety drivers of travel set B with both low and high fast charge wear factors. Data for the high range anxiety driver is nearly identical. Comparing these plots to the L1 opportunity charge from home battery wear reported in Figs. 4 and 5, we see that the addition of either L3 opportunity or L2/L3 timed public charging induces minimal additional battery wear when the fast charge wear factor is set to 1. Further, increasing the fast charge wear factor by an order of magnitude is shown to have minimal effect on median year 10 capacity loss. However, when public L3 opportunity charging is elected, it is apparent that the impact of the larger wear factor can significantly affect the capacity loss of select drivers and nearly doubles the median driver's resistance growth.

Overall, however, these effects on battery degradation are seen to have minimal impact on vehicle utility. The utility factor values shown in Figs. 20 and 21 for the low wear factor are all within 1% of those observed for the high wear factor. The solitary exception is

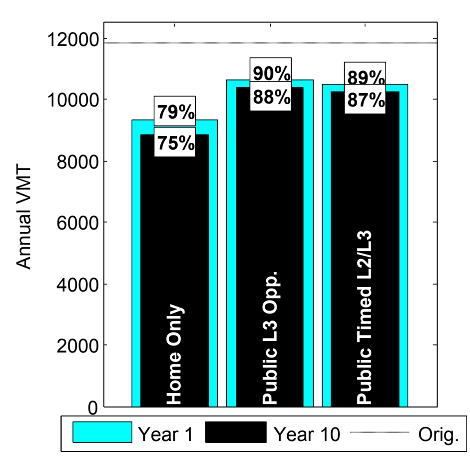

Fig. 20. Average utility achieved by travel sets A and B in the presence of public L3 charging with L1 opportunity charging at home; low fast charge wear factor; low range anxiety (5-mile minimum range margin).

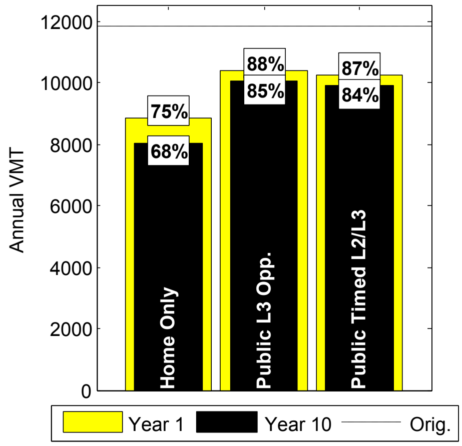

Fig. 21. Average utility achieved by travel sets A and B in the presence of public L3 charging with L1 opportunity charging at home; low fast charge wear factor; high range anxiety (15-mile minimum range margin).

the combination of high range anxiety drivers with public L3 opportunity charging, for which we see the average year 10 utility factor decreasing from 85% to 81% when the fast charge wear factor is increased 10-fold.

In Fig. 22 we compare the added benefit of public L3 opportunity charging over public L2 opportunity charging. For the majority of trip histories, we find that the added benefit of L3 infrastructure over L2 infrastructure is marginal under the constraints we impose. This is primarily due to our restrictions around changing driving behavior; specifically, the fact that we disallow the extension of existing stops or the addition of new stops to charge the vehicle.

4. Discussion

A word on the impacts of uncertainty on this study is merited. Although some parameter uncertainty exists in the underlying historical drive and climate data employed in this study, the main

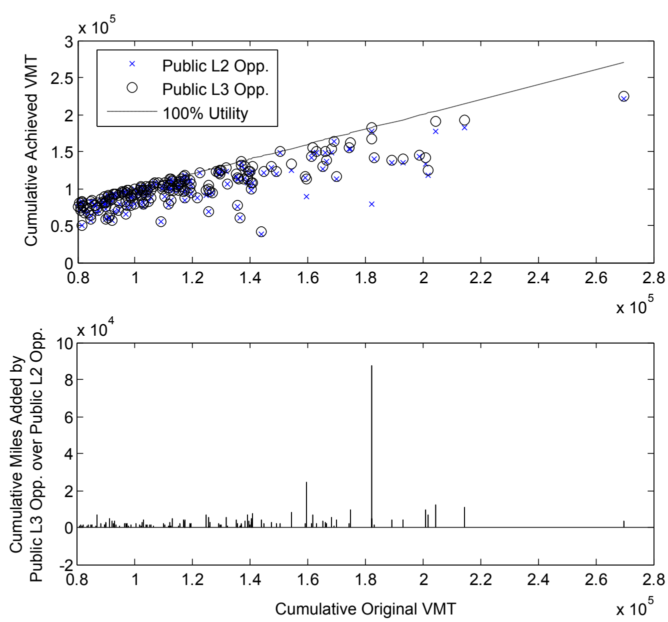

Fig. 22. Comparison of public L2 and L3 opportunity charging for high range anxiety drivers (15-mile minimum range margin), low fast charge wear factor.

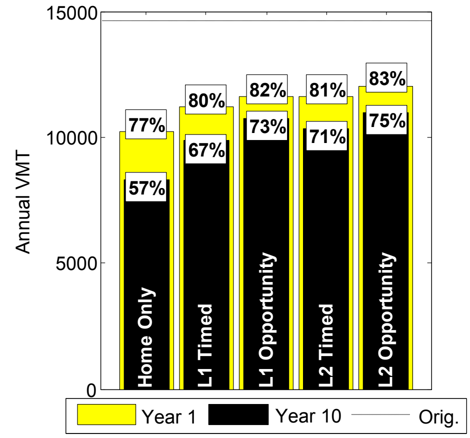

Fig. 23. Average utility achieved for the quartile of travel patterns within travel set C showing the greatest benefit of workplace charging for home-only L1 opportunity charging, and home-only L1 opportunity charging plus four different work charging scenarios; high range anxiety (15-mile minimum range margin).

source of uncertainty herein is structural. Principle structural uncertainties include our approach to modeling human tour decisions, our method of computing vehicle energy consumption, and the battery performance and life models employed. Quantifying the level of uncertainty present in our modeling of human tour decisions is challenged by the need for large amounts of data on the real-world tour decisions of BEV drivers. However, the study of range anxiety conducted herein does illuminate the possible effects of tour decision inaccuracy. The additional aspect of drivers changing tours in response to infrastructure will be addressed in a future study. The second factor, our computation of vehicle energy consumption, is applied consistently across all scenarios herein. Thus, while it is expected to affect the absolute vehicle utilities calculated herein, it should not significantly affect the relative impacts of different charge strategies and range anxieties. Improving the accuracy of battery performance and life models to account for cell-to-cell variation within a pack and better ascertain the impacts of fast charging on battery wear will be a major focus of additional study. Despite these uncertainties, however, the following findings are telling as to the relative impact of the varied charge strategies and range anxiety levels considered on overall BEV utility.

When only home charging is available, we find that L1 opportunity home charging provides less battery wear and similar thru-life utility when compared to either timed or opportunity L2 home charging. This is encouraging for increasing BEV adoption, as it can decrease the initial financial costs of a BEV by eliminating the requirement to purchase a L2 charger and upgrade electricity service. Recurring costs may be increased for customers on aggressive time-of-use utility rate structures with drive patterns that result in significant on-peak charging times, however.

For many commuter drivers in travel set C, we see minimal to no gain in achieved VMT due to the addition of workplace charging. While these drivers are drawing considerable amounts of charge energy from workplace chargers (which may prove economically advantageous to said drivers if the cost of charging at work is less that at home), the low coincidence of work days and long travel days, as well as the limited amount of additional daily range provided by workplace charging when also charging at home (constrained primarily by the morning commute distance) often marginalizes the added annual utility. Select drivers with longer commute distances, however, can greatly increase their achieved VMT with workplace chargers. Of the 68 commuters analyzed, 17 (25%) were found to show more than a 10% increase in year-10 BEV utility. The average utility of this subset for home-only charging and

each of the four workplace charging strategies is presented in Fig. 23. Note that the average year-10 utility increases from 57% to 75% with the addition of workplace L2 opportunity charging. For such drivers, workplace charging may therefore be seen as an enabler for BEV ownership. Similarly, workplace charging may enable BEV ownership for drivers without access to at-home charging (e.g. drivers living in multi-unit dwellings, though this scenario has not yet been studied). Accordingly, dedicated workplace charging infrastructure for the most relevant BEV commuters may be well merited.

Ubiquitous public charging, on the other hand, can offer significant benefit to many drivers, high mileage drivers being most impacted. Under our restrictions that vehicle park times cannot be increased nor can new park events be added to increase public charge time, we see diminishing returns of utility with increased charge power: On average, L1 public charging increases utility over no public charging by ~6%–~9%, L2 by ~9%–~15%, and L3 by ~11%–~17%. Because the difference in utility between L1 and L2 public infrastructure is significant but the difference in cost is likely marginal, it would be advisable to elect to install L2 public charging over L1. However, the difference in cost of upgrading to DC fast chargers (L3) (due to the cost of chargers, electrical service upgrades, and resultant utility demand charges) can be extreme. While the added utility achieved by DC fast charging in this study would appear to discourage the broad installation of such infrastructure, it should be noted that DC fast charging is likely most valuable when drivers are allowed to more freely change their travel in response to available infrastructure than we address herein. Properly analyzing optimal DC fast charging infrastructure deployments is the subject of on-going BLAST-V analysis.

Increased range anxiety was regularly shown to decrease vehicle utility. Increasing access to charging infrastructure partially compensated for range anxiety. In year 10, where results were most sensitive, high range anxiety drivers who enforced a 15-mile minimum range buffer yielded utility factors 7%–10% less than those of low range anxiety drivers who enforced a 5-mile minimum range buffer when only home charging was available. When workplace or public charging infrastructure was added, the difference in the average achieved utility factors of high and low range anxiety drivers fell to 3%–4%.

Across most scenarios and travel patterns, battery wear was unaffected by range anxiety and the variants of home, workplace, and public charging investigated herein. The single exception was in our exploration of public DC fast charging where sensitivity to high charge rate was modified. Where batteries are highly sensitive to high charge rates, we found that ubiquitous public DC fast charging could significantly affect battery degradation. However, this had little impact on utility.

5. Conclusions

For BEVs with a window-sticker range of ~75 miles, as is most typically offered today, we find that low power (L1) home charging offers considerable utility (86–90% of desired miles, on average) to well-suited drivers (27% of our driver sample). Increasing home charging power above L1 has little to no positive impact on BEV utility for most drivers. Adding workplace charging is shown to offer significant benefit to select commuters–increasing average year-10 utility from 57% to as high as 75%, but most commuters see little to no benefit. Alternatively, adding access to public L2 charge infrastructure can bring many lower mileage drivers near 100% utility and greatly increase the VMT achieved by many high mileage drivers as well. Upgrading public infrastructure to DC fast chargers (L3) yielded little additional benefit under the assumptions herein, but merits further investigation under scenarios where drivers are freer to adapt their behavior to available infrastructure. Note that these trends only apply to ~75 mile BEVs; PHEVs and BEVs with different all-electric range may yield significantly different findings.

Across these scenarios, we found that driver range anxiety has a significant effect on achieved utility. In our home-only L1 opportunity charging scenario, we saw that the average high range anxiety driver achieved 4% and 8% lower utility factors in years 1 and 10, respectively, than the average low range anxiety driver. While adding charge infrastructure was seen to reduce the impact of range anxiety and increase utility, as expected, other lower cost means—such as improving travel and energy consumption predictions—are available to reduce driver range anxiety directly and improve utility as well.

Considered collectively, though, these findings motivate further investigation of public charging infrastructure, as it has been shown herein to be capable of substantially increasing vehicle utility directly and is also expected to reduce range anxiety. While our results have highlighted the potential gains of mass public infrastructure deployments, we have not yet quantified the relationship between vehicle utility and infrastructure cost for smaller, more realistic infrastructure rollouts. Further, we have not yet explored the true value of DC fast charging where drivers adapt travel patterns to the available infrastructure. Both of these topics are the subject of ongoing BLAST-V analysis, along with geo-spatial analysis to identify high-value infrastructure locations, and will be discussed in a future publication.

Acknowledgment

This study was supported by Dave Howell and Brian Cunningham of the Energy Storage, Vehicle Technologies Office, Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy. The use of the battery degradation and FASTSim tools, both developed at the National Renewable Energy Laboratory under funding from the U.S. Department of Energy's Vehicle Technologies Program, was critical to the completion of this study. Special thanks to Kandler Smith for developing and supporting the integration of the battery degradation model, and Ahmad Pesaran, the National Renewable Energy Laboratory's Energy Storage team leader, for his continual guidance.

Glossary

BEV	battery electric vehicle
BLAST-V	Battery Lifetime Analysis and Simulation Tool for Vehicles
L1	level 1 (1.5 kW to the battery)
L2	level 2 (6.5 kW to the battery)
L3	DC fast charging (50 kW to the battery)
SOC	state of charge
VMT	vehicle miles traveled

References

[1] J. Neubauer, E. Wood, A. Brooker, J. Power Sources 209 (2012) 269–277.
[2] J. Neubauer, E. Wood, A. Brooker, J. Power Sources 236 (2013) 257–364.
[3] J. Neubauer, A. Pesaran, SAE Tech. Pap. (2013), http://dx.doi.org/10.4271/2013-01-0500, 2013-01-0500.
[4] J. Neubauer, A. Pesaran, A Techno-economic Analysis of BEVs with Fast Charging Infrastructure, EVS27, Barcelona, Spain, November 2013.
[5] J. Neubauer, E. Wood, J. Power Sources (2014) in press.
[6] J. Neubauer, E. Wood, SAE Tech. Pap. (2013), http://dx.doi.org/10.4271/2013-01-1453, 2013-01-1453.
[7] Traffic Choices Study – Summary Report, Puget Sound Regional Council, April 2008.